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Passive scalar dispersion along porous stratum with natural convection

Chenglong Hu[*], Ke Xu[†], Yantao Yang[‡]

The migration of passive scalars along subsurface porous strata, such as radioactive contaminant spreading and subsurface colloid migration [1], can bring long-range environmental and geochemical impacts[2]. The horizontal solute transport can be further complicated by the intrinsic geothermal gradient, since natural convection in porous media, or the Rayleigh-Darcy convection, can develop due to the unstable geothermal gradient[3]. In this study we investigate how natural convection driven by vertical thermal gradient regulates the horizontal dispersion of passive solute scalar in a porous stratum.

A series of two-dimensional Rayleigh-Darcy flows are simulated for gradually increasing Rayleigh number Ra, which covers the conduction regime, the steady convection-roll regime, and the turbulent regime. At the fully developed state fro each case, the horizontal dispersion of solute is examined by introducing a horizontal confined high solute concentration column and then following the horizontal spreading of the solute field. The horizontal dispersion efficiency can be quantified by the dispersion coefficient $\hat{D}$, which is calculated through fitting the vertically averaged solute field with the exact solution of horizontal one-dimensional diffusion equation.

The key findings are presented in figure 1. We found that although the vertical heat Nusselt number Nu monotonically increases with Ra, the horizontal dispersion coefficient ratio $\hat{D}/D_0$ increases in the steady convection-roll regime at intermediate Rayleigh numbers and saturates in the turbulent state at high Rayleigh numbers. We reveal that at the convection-roll regime the horizontal dispersion is controlled by the roll structures which extend the whole height of porous stratum, while at the turbulent regime it is controlled by the plume structures near the boundaries. The different behaviours of $\hat{D}/D_0$ and the corresponding scalings versus Ra can be understood by the scaling laws of the relevant characteristic velocity and length at different regimes.

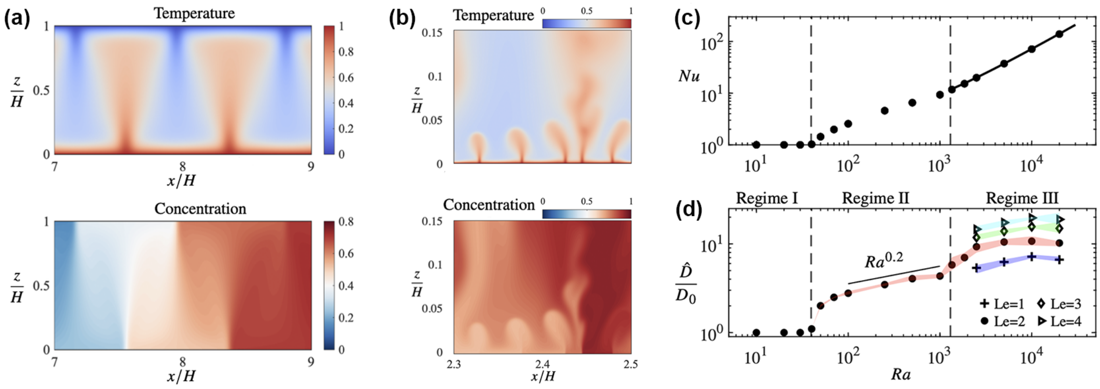

Figure 1: (a) The instantaneous fields of temperature and concentration for $Ra = 500$ and $Le = 2$. (b) The instantaneous fields of temperature and concentration for $Ra = 20000$ and $Le = 2$. (c) The vertical thermal Nusselt number Nu versus the Rayleigh number Ra. (d) The ratio of horizontal diffusion coefficient to molecular diffusivity $\hat{D}/D_0$ versus Ra. Note in (a) and (b) different size of regions are shown to highlight the different structures.

[*] State Key Laboratory for Turbulence and Complex Systems, and Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, P.R. China

[†] Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing 100871, P.R. China; Institute of Energy, Peking University, Beijing 100871, P.R. China

[‡] State Key Laboratory for Turbulence and Complex Systems, and Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, P.R. China; Laoshan Laboratory, Qingdao 266299, Shandong, P.R. China

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